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A NEW PARADIGM FOR AUTONOMOUS SPACECRAFT: FROM RESEARCH TO DEPLOYMENT

Lorraine M. Fesq, ASTERIA Program/Project Manager
Jet Propulsion Laboratory, California Institute of Technology.

IAA Low Cost Planetary Missions
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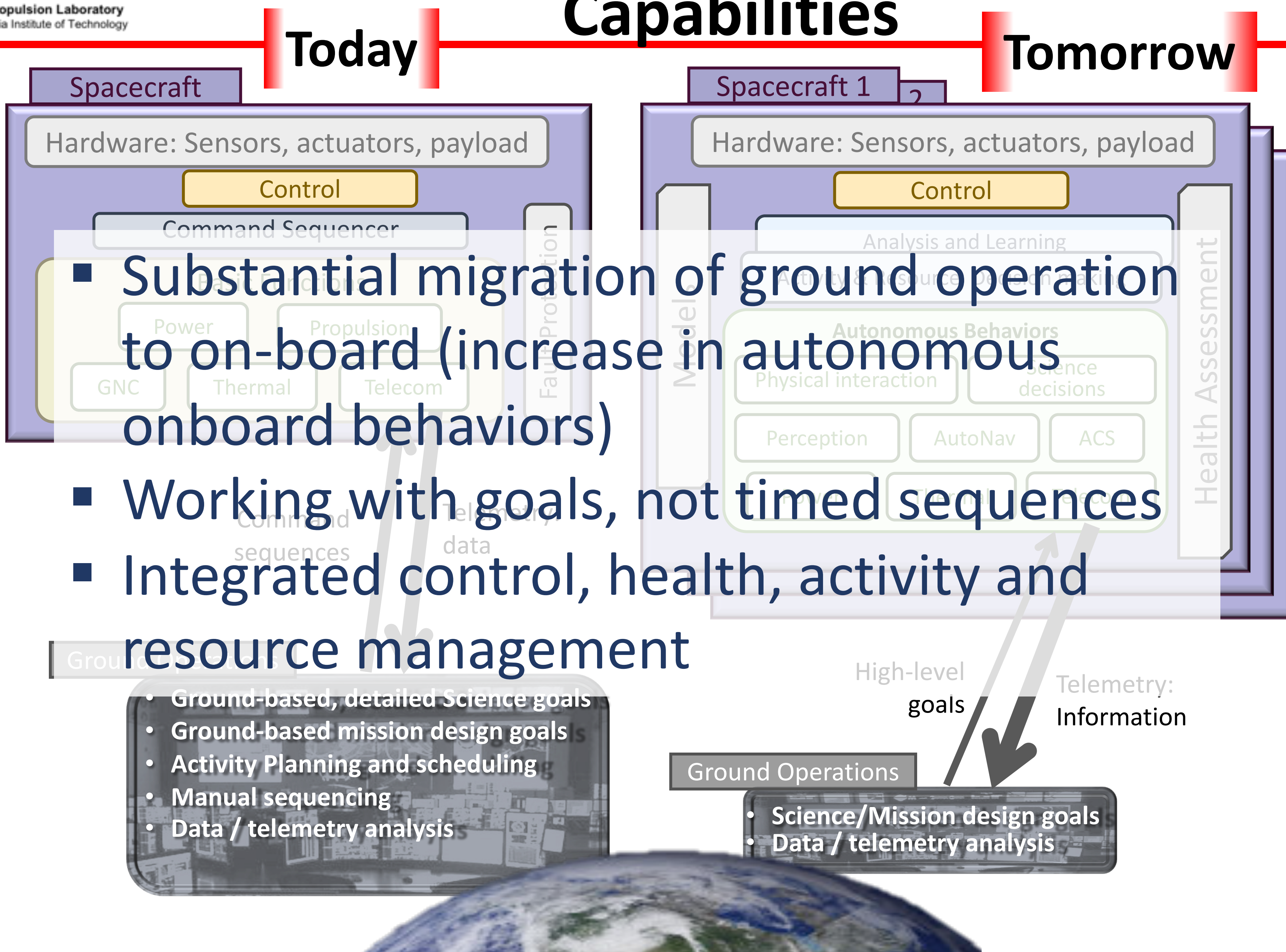
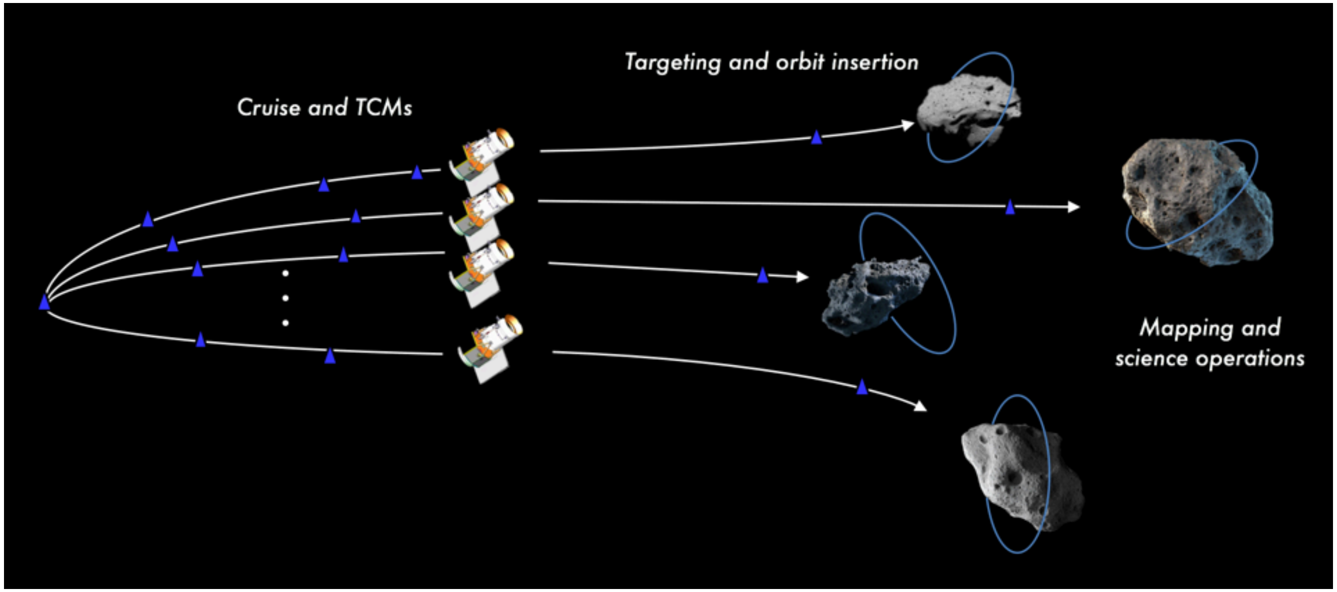
From Today to Tomorrow's Space-based Capabilities

- Substantial migration of ground operation to on-board (increase in autonomous onboard behaviors)
- Working with goals, not timed sequences
- Integrated control, health, activity and resource management



NEO Mapper Demo

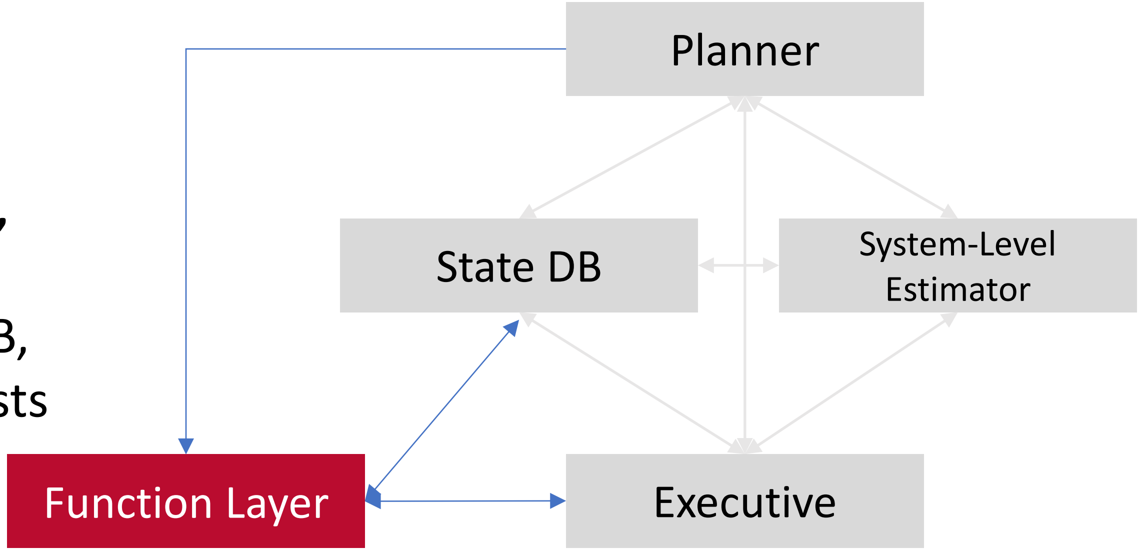


- **Goal-based commanding demo to demonstrate concurrent execution of:**
  - **Mapping**
  - **Stationkeeping**
  - **Orbit knowledge**
  - Telecom & autonomous file management
  - ACS health monitoring
- **At NASA JPL in DARTS simulation and Caltech CAST using physical simulators**

System-Level Autonomy Framework

Achieving a goal can be fully specified on-the-ground or assembled on-board.

Function Layer (*e.g.* Autonav, other subsystems): Runs commands, informs state DB, responds to Planning requests



The systems achieves independent *goals* using hierarchical *task networks.*

- ASTERIA

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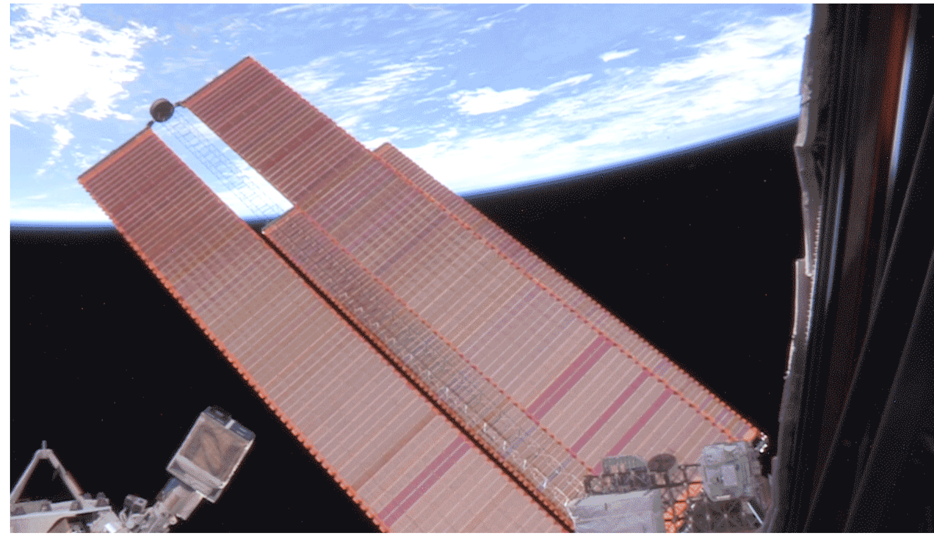
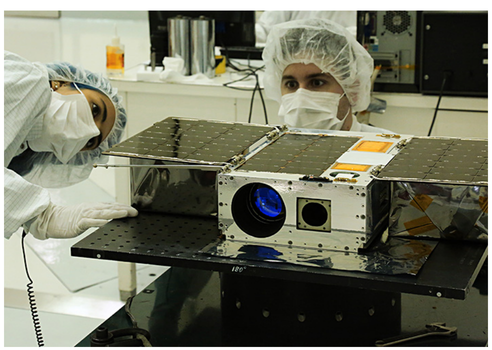
Using the ASTERIA* Cubesat to demonstrate In-Space Autonomy

*Arcsecond Space Telescope Enabling Research In Astrophysics

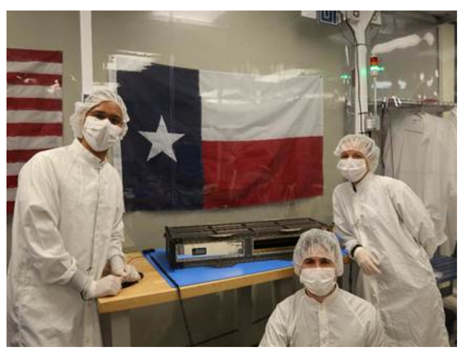
- 6U CubeSat built, tested, operated by JPL
- Collaboration with MIT’s Sara Seager, PI
- Demonstrated **pointing stability of <0.5 arcseconds RMS** over 20 minutes
- Demonstrated focal plane **thermal stability of ±0.01 K** over 20 minutes
- **First CubeSat to detect an exoplanet!**



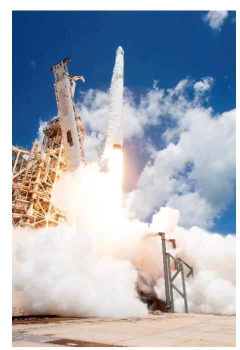
Deployed from International Space Station



Development
Dec 2014 through Jun 2017



Delivery
1 Jun 2017



Launch
14 Aug 2017

Deployment
20 Nov 2017

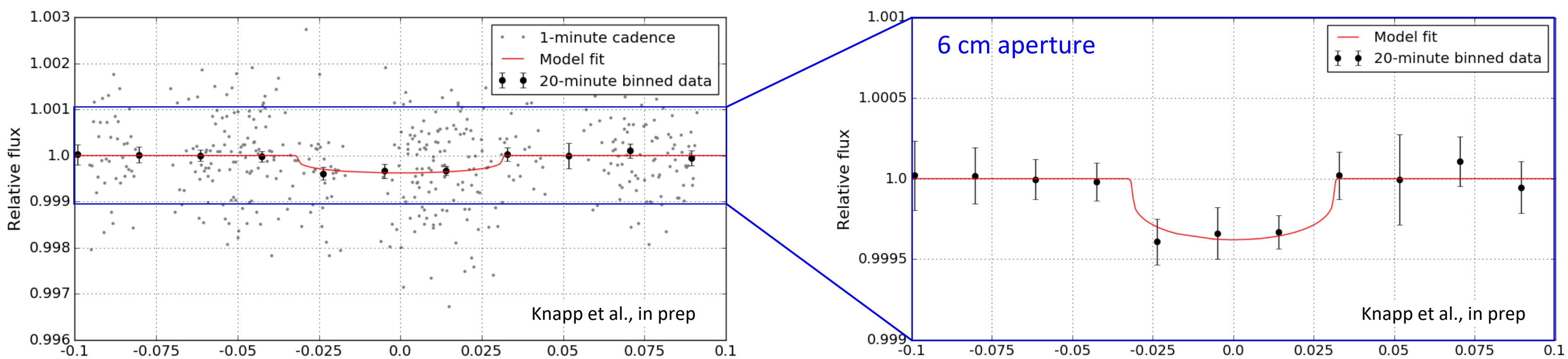
Operations lifetime
Exp. through Apr 2020

Completed prime mission Feb. 2018; now used for <u>five</u> experiments

#1. Science Observations

Perform new ASTERIA observations to extend mission science.

- ASTERIA has demonstrated unprecedented photometric precision for a CubeSat mission.
- Current science goals will **shift from follow-up of previously detected planets to discovery of as-yet unknown additional planets**. The spacecraft is uniquely suited to perform long-term monitoring of stars such as alpha Centauri for small transiting planets.
- **The discovery of a transiting Earth-sized planet around alpha Cen A and/or B would be of the highest scientific value** as such a planet would be our closest exoplanetary neighbor orbiting a Sun-like star.



Observed known transit of 55 Cancri e transit

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#2. Background on Commanding Spacecraft

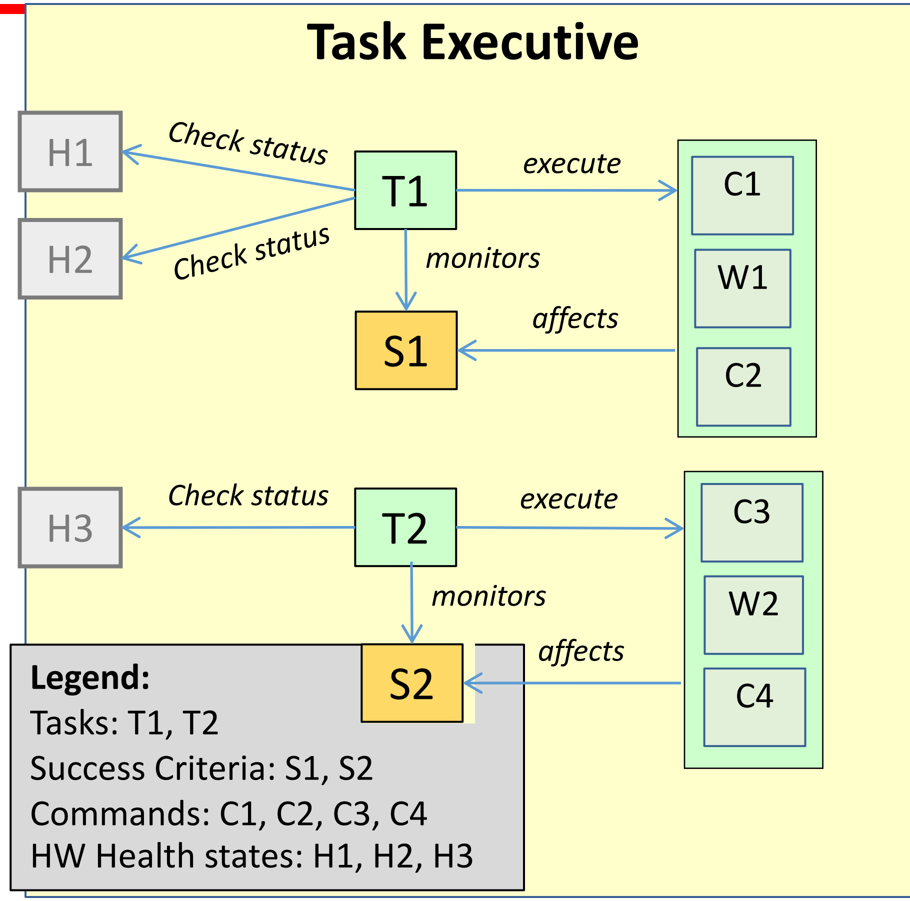
Command sequencer

Start of sequence

- Issue command C1
- Wait W1 seconds
- Issue command C2
- Issue command C3
- Wait W2 seconds
- Issue command C4

End of sequence

- Sequence success/failure unknown until telemetry analyzed on Ground
- Works well for predictable, fault-free scenarios
- If fault occurs, SAFE
- Human-intensive, not viable for 100s of spacecraft

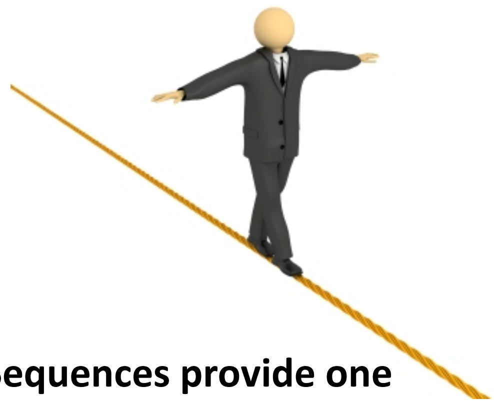


- Task = cmd + pre- and post-conditions
- If fault occurs, handle on-board. Safing is last resort
- Enabling for planetary swarms and constellations

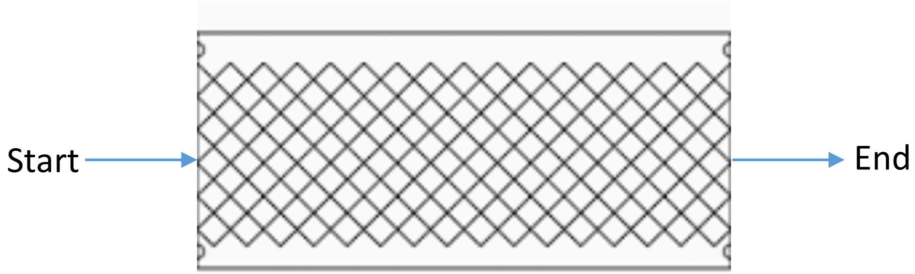
ASTERIA Experiment #2. Multi-mission EXECutive (MEXEC) Closed-Loop Task Execution

Shift the paradigm to operate spacecraft from timed sequences to closed-loop task execution.

- Goal: Demonstrate effectiveness of “task networks” (tasknets) and to increase efficiency and robustness of future space missions
- Tasknets
  - Check preconditions and postconditions of tasks
  - Simpler commanding – WHAT not HOW
  - Reduces down-time on space vehicle
  - Robust on-board execution - space vehicle determines order and timing of activities based on current conditions and handles unexpected events



Sequences provide one execution path

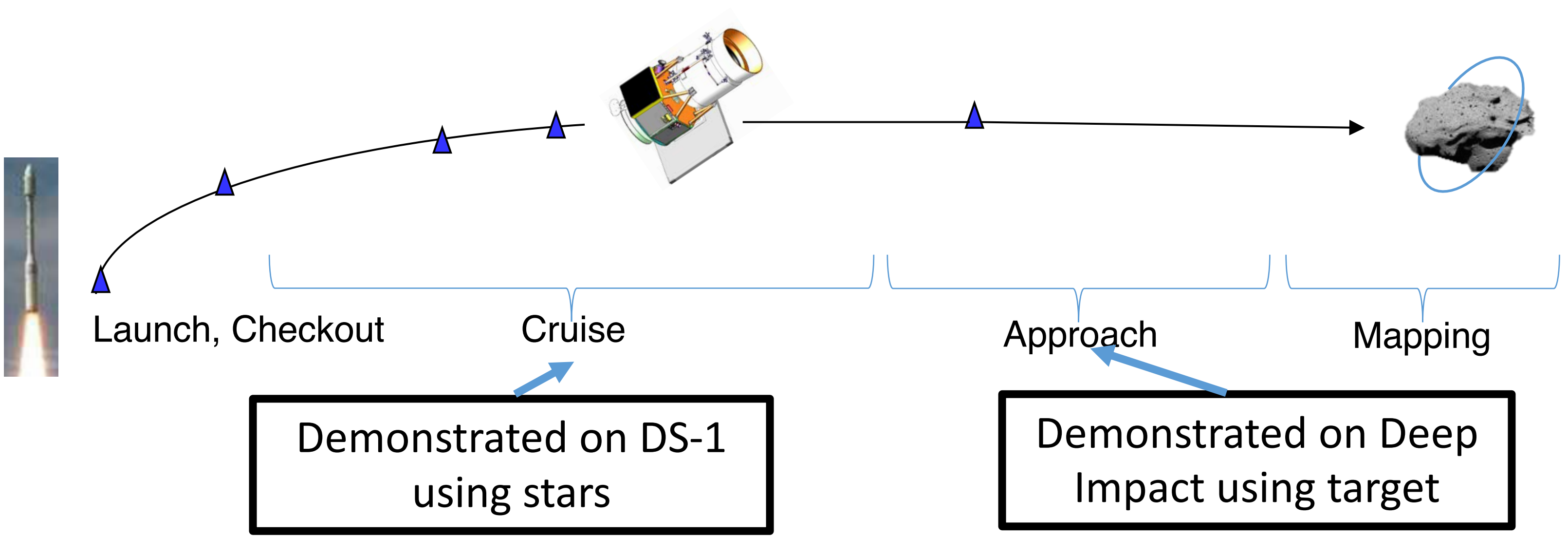


Tasknets provide flexibility to achieve activities

MEXEC code is being flight-certified, integrated into ASTERIA FSW, validated on testbed and uplinked in Spring 2019.

#3. Autonomous Navigation (AutoNav) Overview

- Optical images of objects are used to estimate spacecraft position, velocity, and attitude
- AutoNav: All ground-based Optical Navigation techniques transferred to spacecraft and automated
- Involves 3 steps
  1. Image processing: Automatically identifies stars or target body in camera FOV and performs center-finding
  2. Orbit determination (OD): Filter combines images and other spacecraft information such as thrusting, attitude knowledge, etc. to determine complete spacecraft position state
  3. Maneuver planning and execution: Maneuvers computed at pre-specified times to retarget s/c to reference trajectory



Adapted from a slide by S. Bhaskaran

ASTERIA Experiment #3. Autonav

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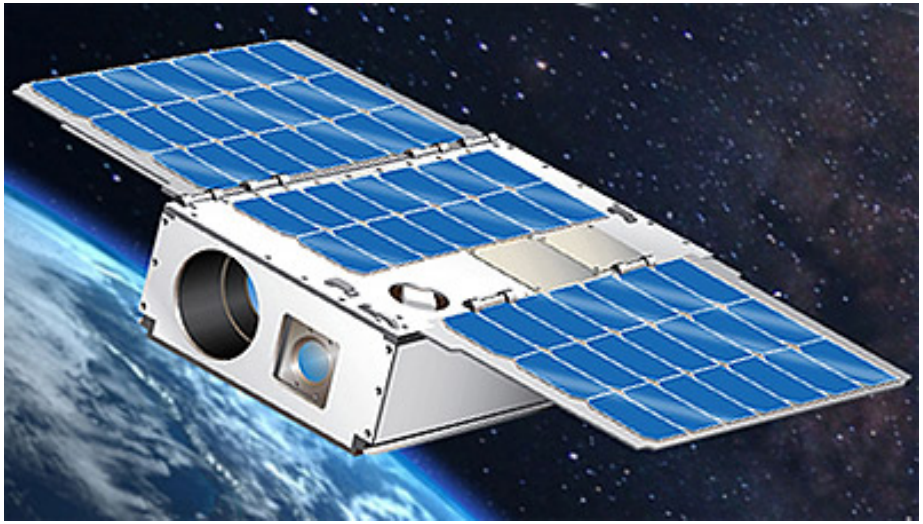
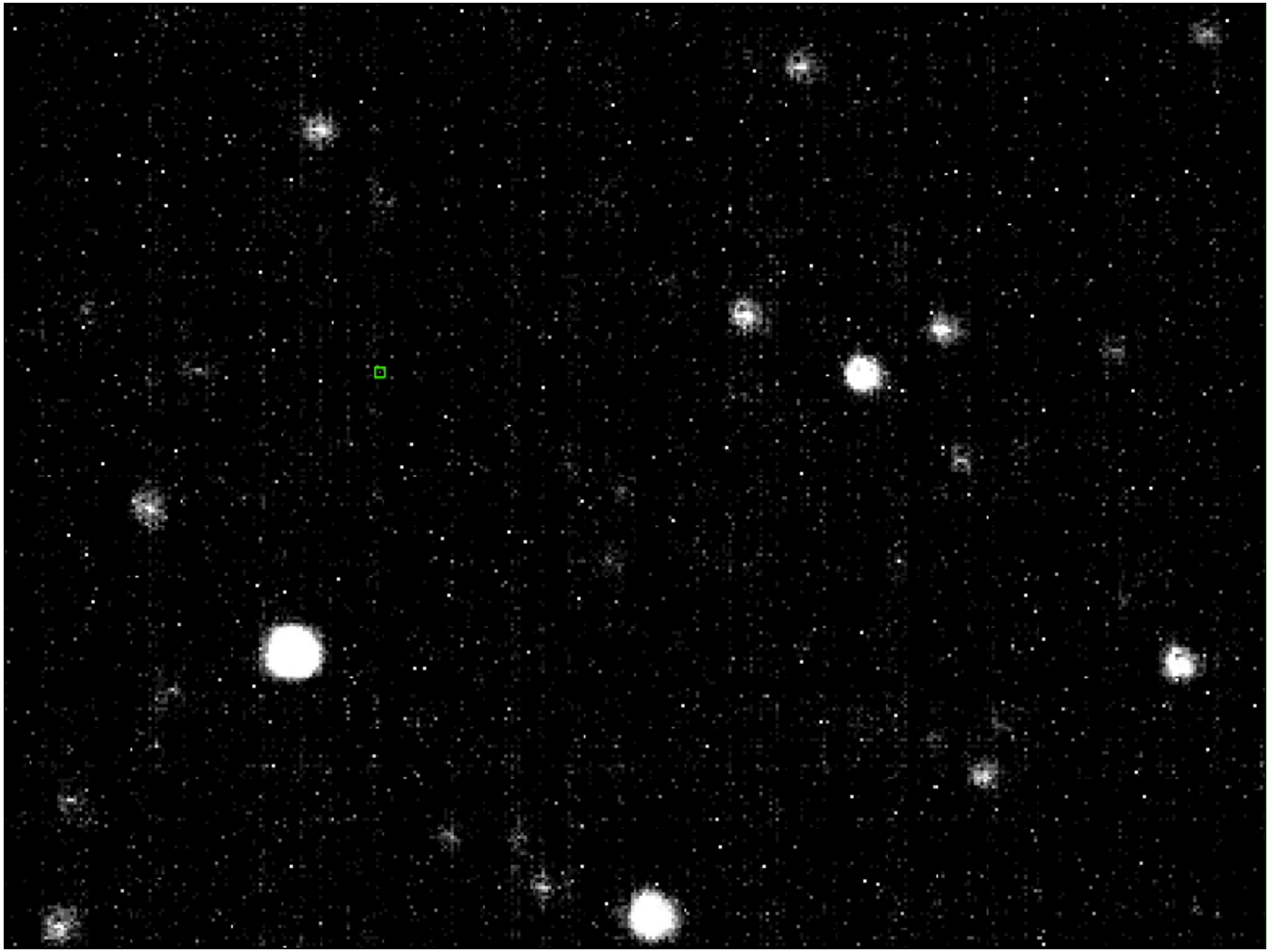
Demonstrate onboard orbit determination in Low Earth Orbit (LEO) without GPS using Autonav.



- Demonstrate a fully independent means of spacecraft OD for Earth orbiters with only passive imaging using ASTERIA camera.
- Enable future missions to navigate in GPS-denied environments.
- Approach:
  - ✓Image a small body to confirm camera quality
  - ✓Image geo-stationary spacecraft to assess feasibility
  - ✓Run Autonav software on testbed for metrics
  - o Integrate Autonav into ASTERIA FSW, test and upload.

JPL's Autonav software is being integrated into ASTERIA FSW, validated on testbed and uplinked in late Summer 2019.

Geobird Observations – 4 images



Geostationary spacecraft have been observed using ASTERIA's camera for use by Autonav software

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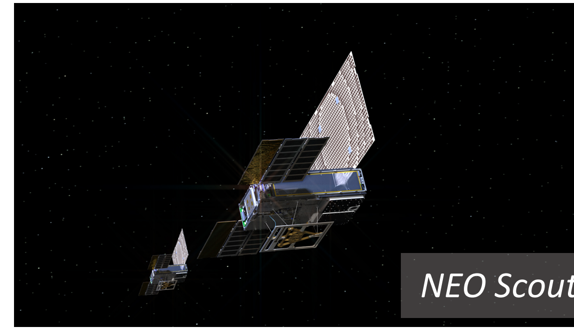
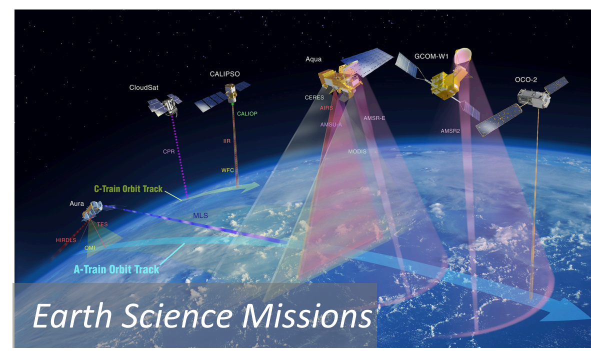
Summary

- Future missions must autonomously detect and respond to in situ conditions and events
- Software framework needed to coordinate all autonomous functions on-board - FRESCO
- ASTERIA is an ideal platform for experiments
  - Two years remained life past prime mission
  - Flight software is changeable
  - Highly capable spacecraft and payload
- Experiments being conducted on ASTERIA
  1. Exoplanet exploration
  2. Task-level execution
  3. Autonav for LEO w/o GPS
- These capabilities are relevant to planetary, astrophysics and Earth Sciences


NEO Scout


Lunar Lander



Earth Science Missions

ASTERIA will demonstrate task-based commanding and execution Summer 2019 and autonomous optical navigation Fall 2019

Acknowledgements

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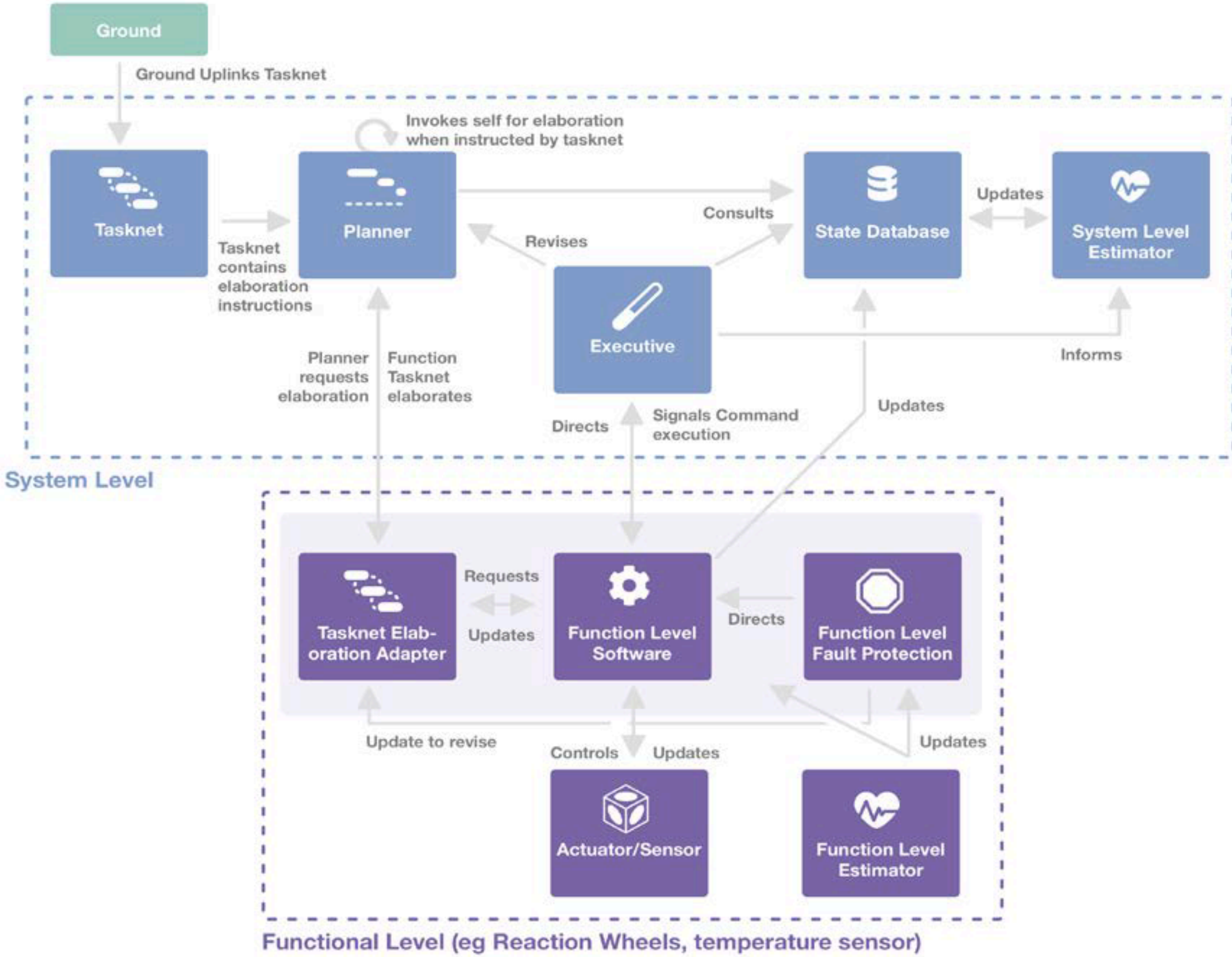
- **We Thank**
  - ASTERIA Principal Investigator Sara Seager (MIT) for supporting our efforts to use the spacecraft for these technology demonstrations while continuing to perform exoplanet exploration science;
  - The JPL ASTERIA team: Brian Barker, Brian Campuzano, Peter DiPasquale, Kyle Hughes, Ansel Rothstein-Dowden, Jose Carlos Abesmis, Jules Lee, and Kristine Fong, who continue to keep the spacecraft healthy and operational;
  - Chris Pong, Shyam Bhaskaran, Patrick Doran, David Ardila, Aadil Rizvi, Michael Starch, Tomas Martin-Mur, Professor Soon-Jo Chung and Sorina Lupu (Caltech) who are supporting development of the technology demonstrations;
  - Brice Demory (University of Bern) for science data analysis;
  - Ben Malphrus and his team from Morehead State University for continued ground station support.

FRESCO



Ground
Ground Uplinks Tasknet
Tasknet
Tasknet contains elaboration instructions
Planner
Invokes self for elaboration when instructed by tasknet
Revises
Consults
State Database
Updates
System Level Estimator
Executive
Informs
Planner requests elaboration
Function Tasknet elaborates
Directs
Signals Command execution
Updates
System Level
Tasknet Elab-oration Adapter
Requests
Updates
Function Level Software
Directs
Function Level Fault Protection
Update to revise
Controls
Updates
Updates
Actuator/Sensor
Function Level Estimator
Functional Level (eg Reaction Wheels, temperature sensor)

FRESCO

Tasknet: Data structure that encapsulates possible spacecraft activities
Planner: Responsible for scheduling and planning tasks based on their details
Executive: Responsible for intelligent execution and monitoring of scheduled tasks.
State Database: Database with component status and abstracted system-states used in decision-making
System-Level Estimator: Estimators that inform decision- making using states from different aspects of the flight system. E.g., system health monitoring.
Function-Level Software: Software, including hardware controllers or functional autonomy. Can be responsible for local fault handling.
Function-Level Estimators: E.g. filters or local voting systems used for local decision-making.
Actuators/sensors: E.g. Reaction Wheel Assembly, motors. Sensors for temperature, voltage, etc.
Function-level Tasknet Component: An interface to the Planner that allows for Function-Level Software to make plan change requests.